Chapter 10

Diffraction of Light & Spectroscopy

The 17th C. marks the start of a stunning change in the way we view the physical nature of the world around us. Gravity, motion, light, electricity, and magnetism, came under scrutiny. In that century much that was known about light was re-examined. Colours were recognized as an integral part of ”white” light (Newton). Two different views of the nature of light were developed, tiny particles (Newton) or longitudinal waves (Huygens). Newton explained colours by postulating different sizes for the tiny particles (blue was the smallest size). Huygens had no explanation for colours. Until the end of the 18th C. Newton's view was predominant. Then, at the beginning of the l9th C. Thomas Young did an experiment that changed things drastically. His double slit experiment could be explained properly if light was a longitudinal wave since only a wave could diffract and have constructive/destructive effects. Moreover, Young showed that colours were related to wavelengths. His experiment and his conclusions created strong controversy. Fifteen years after the ”double slit” experiment, Young and Fresnel realized that light had to be a TRANSVERSE WAVE in order to explain polarisation effects. Since then, light as a transverse wave has been the prevailing view. The early part of the 20th C. marks another stunning change in our view of the physical world. Quantum ideas and the ”discrete” nature of the atomic world have fueled great changes in physics, chemistry, and biology. We examine one of the causes and early triumphs of these ideas as we look at ”discrete” colours in the light from discharge tubes.

Objective

1. To measure the wavelength of light emitted by the discharge tube and to identify the gas contained in the tube.

Apparatus Spectrometer, diffraction grating, discharge tubes, power supply.

10.1 Introduction

Many of the properties of light can be explained only if light is treated as a wave. Fig. 10.1 shows laser light incident on a barrier with two slits. A pattern of many bright spots is observed on the screen (not just two spots which one could expect if light travelled along a straight line).

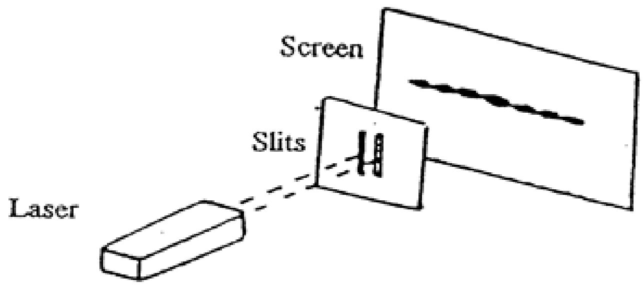

Figure 10.1

The pattern can be explained by the phenomenon of interference of waves. Recall from the sound experiment that two waves interfere constructively if a crest of one wave occurs at the same place as the crest of the second wave. Destructive interference occurs when the crest of one wave coincides with the trough of the other wave. Each slit in Fig. 10.1 can be treated as a source of a wave. The waves from two slits produce a bright spot on the screen when two waves interfere constructively. This happens when the distances travelled by two waves differ by one or two, or three, or $n\lambda$ wavelengths. If the slits are separated by the distance d (Fig. 10.2), then for a difference of one wavelength,

$$\sin\theta_1 = \lambda/d$$

If the distance travelled by the two waves originating from two slits differ by 2λ then a second bright spot occurs on the screen when $\sin\theta_2 = 2\lambda/d$. In general, the n-th bright spot occurs for the angle given by

$$\sin\theta_n = n\frac{\lambda}{d} \tag{10.1}$$

When two slits are replaced by a diffraction grating which contains many slits then the maxima occur at the same positions on the screen as for the two slits, but the peaks are much narrower (Fig. 10.3). Thus the resolution of the pattern of the bright spots is higher when a diffraction grating is used. A diffraction grating is produced by making scratches in a glass plate.

The unscratched parts of the glass are transparent for the light and act as slits. The scratches block the light. A diffraction grating can also be made by taking a photograph of many black lines. The negative of the photograph can serve as a grating.

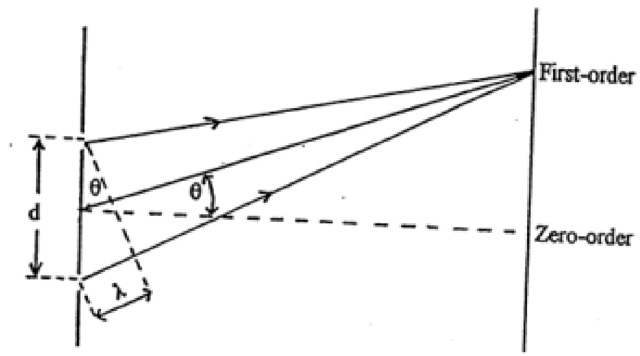

Figure 10.2: Constructive interference from double-slit diffraction.

Figure 10.3: Narrowing of Interference with more slits.

The laser light contains only one wavelength (monochromatic light). If the laser light in Fig. 10.1 is replaced by polychromatic light (mixture of different wavelengths) then the waves of different λ interfere independently. According to equation 10.1 waves of longer wavelength are deviated more (larger θ). Fig. 10.4 shows the diffraction pattern for the mixture of the violet, blue and red light.

10.2 Prelab Exercises

Read through Experimental section first.

1. Explain the role of the diffraction grating in the spectroscope.
2. Why must the telescope be focused at infinity?
3. The first order maximum for red light ($\lambda = 635.0nm$) is observed at exactly 12 degrees. At what angle would the second order maximum be observed for the same wavelength?
4. Read the angular Vernier scales in Figure 10.5. Report the angles in degrees/minutes as well as decimal degrees (for example $45°16'$ and $45.27°$)

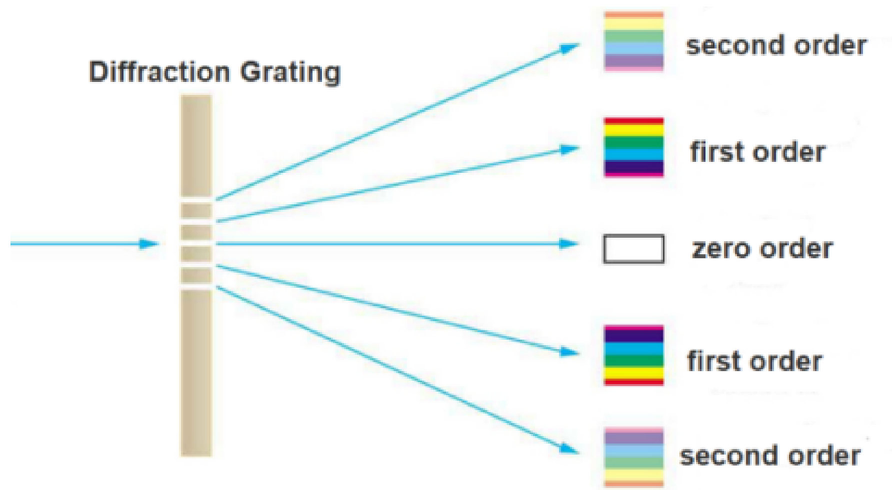

Figure 10.4: Diffraction of multiple wavelengths through a grating.

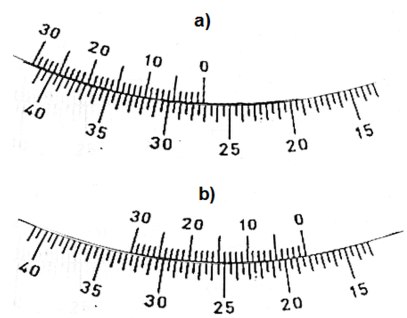

Figure 10.5: Sample Vernier scales for prelab exercise

10.3 Experimental

To study the diffraction pattern, a spectrometer is used. The spectrometer consists of a collimator, a diffraction grating and a telescope (Fig. 10.6).

The light to be analyzed is sent through a narrow slit of adjustable width. The slit is at the focal point of the converging lens so that the rays of light emerging from the collimator are parallel. The diffraction pattern is observed through the telescope. The telescope contains two lenses called an objective and an eyepiece. The telescope can be rotated to observe different orders of the bright spots.

An angular Vernier scale, (Fig. 10.7) enables one to read the angle of rotation of the telescope to the nearest minute of arc.

Use the Vernier scale as follows. First, read the angle on the main scale indicated by the zero of the Vernier scale (20.5°) in Fig. 10.7). Then find the division of the Vernier scale

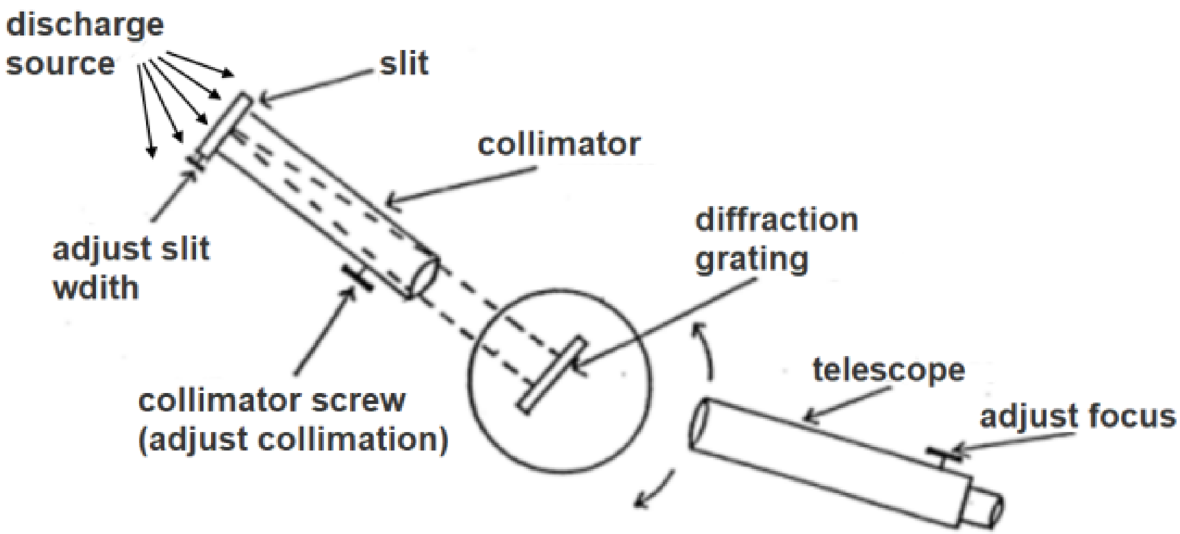

Figure 10.6: Experimental setup.

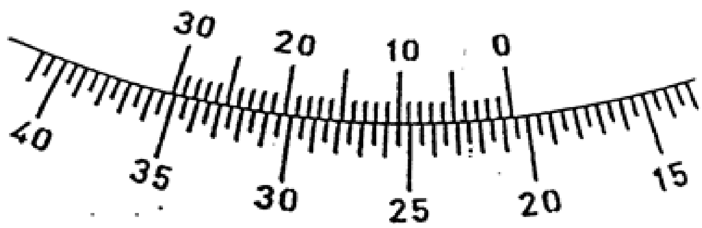

Figure 10.7: Angular Vernier scale.

which coincides with any division of the main scale (10′ in Fig. 6). Add the reading of the vernier scale to the angle read on the main scale (20°40′). **A screw on the bottom of the spectrometer serves to lock the telescope at the given position. A second screw serves to adjust the final position of the telescope. The adjustment screw works only if the lock screw is tightened.**

As a source of polychromatic light, a discharge tube is used (Fig. 10.8). The light emitted by the tube depends on the gas in the tube. A very high voltage (5000V) is applied across the tube. **DO NOT TOUCH THE TUBE WHEN IT IS OPERATING**.

10.4 Measurements and Calculations

1. Adjust the focus of the telescope on a distant object (such as through the window) by turning the screw knob mounted on the side of the telescope (Fig. 10.6). The rays of light coming from this distant object are parallel (for our purposes).

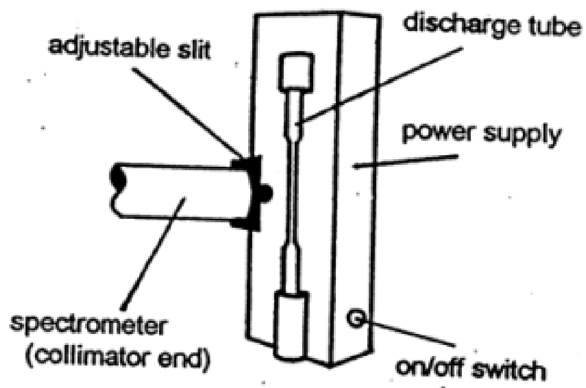

Figure 10.8: Discharge tube apparatus.

2. Mount one of the two gas discharge tubes you will use in the discharge tube power supply and turn it on.

   Position the slit directly in front of the light emitted by the discharge tube and observe it through the telescope.

   Turn the screw knob on the side of the collimator to obtain a sharp image of the slit as seen through the telescope. When the slit is at the focal length of the collimator lens, the light rays that emerge are parallel. Now both the collimator and telescope will be properly focused.

   The image of the slit should not be too wide since all your spectral lines will also have the same width as the slit. Adjust the slit width by turning the slit screw knob.

3. Place the diffraction grating on the round spectrometer table and make sure it is at right angles to the parallel light rays going from the collimator lens to the telescope lens. Looking through the telescope eyepiece, position the vertical crosshair so that it goes through the image of the slit, the central maximum. The angle on the vernier scale will be your zero reading. Measure all the angles of the spectral lines observed corresponding to the first, n=1 and second, n=2 order maxima. Use equation 10.1 to calculate the wavelengths for all the different coloured spectral lines. Use Table 10.1 at the end of the manual to record your data and calculations.

   The diffraction grating constant, $d = (3.33 \pm 0.2) \times 10^{-6} m$, unless told otherwise.

   Remember that the same sequence of colours or spectral lines will be observed in all orders of maxima, n, although the higher order spectral lines will be fainter and more spread apart. Of course, the wavelength for any given colour will be the same for all n.

4. Match your average wavelength values for each of the spectral lines with the wavelengths for the emission spectra of various gases shown in the program "$line_identify$"

on the desktop of the computer. Do not match by colour. Record the label on the gas discharge tube along with the name of the gas you identified.

Repeat this experiment with the second gas discharge tube provided, recording your data and calculations in Table 10.2.

5. (PHYS1010 Only) In the previous experiments you calculated uncertainties using the rules found in section 0.2.2 of this lab manual. These rules were useful only when operations such as +,- or x or divide were involved.

   Whenever functions such as tan or log are involved, we must use the more sophisticated methods described below. It is likely that now, at the end of the academic year, you are familiar with differentials and partial derivatives and that you are ready to calculate uncertainties for quantities which are more complicated functions of other quantities.

   In general, if a quantity y is a function of variables $x_1, x_2, ..., x_n$, and if these variables are uncertain by $\delta x_1, \delta x_2, ..., \delta x_n$ respectively, then the value of the quantity y is uncertain by δy

   $$\delta y = \frac{\partial y}{\partial x_1}\delta x_1 + \frac{\partial y}{\partial x_2}\delta x_2 + ... + \frac{\partial y}{\partial x_n}\delta x_n$$

   The symbol $\partial y/\partial x_i$, where $i = 1, 2, ..., n$, represents a partial derivative. It means to take the derivative with respect to x_i only and treat all other variables as constants. Let's use the above expression to calculate the absolute uncertainty of the wavelength λ.

   $$\lambda = f(d, \theta) = \frac{d \sin\theta}{n} \quad \text{, where n= constant}$$

   $$\delta\lambda = |\frac{\partial f}{\partial d}\delta d| + |\frac{\partial f}{\partial \theta}\delta\theta| = |\frac{\sin\theta}{n}\delta d| + |\frac{d\cos\theta}{n}\delta\theta|$$

   The θ in the above expression is the angle of the spectral line with respect to angle of the $n = 0$ line. The uncertainty δd of the diffraction grating constant is specified by the manufacturer of the grating ($\delta d = 0.2 \times 10^{-6} m$).

   The absolute value of each term in the above expression is taken because uncertainties are always added and never subtracted.

   The uncertainty $\delta\theta$ is related to the accuracy of reading the Vernier scale on the spectrometer. Theoretically, it is possible to read the angle θ with the accuracy of 1 minute. However, due to some other inaccuracies associated with the measurement of the angle θ, a more reasonable estimate of $\delta\theta$ is probably 3 minutes. Convert 3 minutes to radians to obtain $\delta\theta$. Round off the value to one significant digit only. Determine the uncertainty $\delta\lambda$ for one colour for one gas (for $n = 1$).

   Determine the percentage uncertainty $\delta\lambda/\lambda \times 100\%$.

6. The discrete spectra observed for different gases reflect the discrete (quantized) nature of the energy of electrons in atoms and molecules. Radiation is emitted when electrons

jump to a lower energy state. Bohr showed that the wavelengths of the observed hydrogen emission lines can be fitted to the following formula

$$\frac{1}{\lambda} = R(\frac{1}{l^2} - \frac{1}{u^2})$$

where l and u are integers called quantum numbers of the lower and the upper energy states, and R is the Rydberg constant ($R = 1.097 \times 10^7 m^{-1}$).

The red light emitted by the hydrogen atom corresponds to the transition from the $u = 3$ state to the $l = 2$ state. Use the above formula to compute the value of λ for the red light emitted by the hydrogen atom. Evaluate the agreement between your experimental value of λ and the calculated value of λ.

10.5 Questions

1. If monochromatic light enters the collimator's slit, what would you expect the spectrum to look like? Explain.
2. Is the spectrum formed by polarized and unpolarized light different? Check your answer by placing a polarizer in front of the slit opening.
3. Would a useful spectrum be formed in the experiment if the diffraction grating had only 20 lines per centimeter? Explain.
4. How would the spectrum change if the diffraction grating were not at right angles to the incident beam. Rotate the diffraction grating slowly so that it is no longer perpendicular to the incident beam and note any change in angle of the spectral line with respect to the crosshair in the telescope.
5. If the diffraction grating lines are perpendicular to the collimator's slit, would a spectrum be observed? If so, how would it look like (make a sketch)? Verify this by holding the diffraction grating close to your eye and rotating it while looking at the light from your discharge tube.

END OF LAB

Was this lab useful, instructive, and did it work well? If not, send an email to thatlabsucked@gmail.com and tell us your issues. In the subject line, be sure to reference the your course, the experiment, and session. example subject: *PHYS1010 Linear Motion monday 2:30*. We won't promise a response, but we will promise to read and consider all feedback.

Table 10.1: Diffraction of Light from Gas Tube - Data and Calculations

<table>
<tr><th>Order</th><th>Colour</th><th>Angle (° and ′)</th><th>Angle (° only)</th><th>$\lambda = dsin(\theta_{1,x} - \theta_0)/n$</th></tr>
<tr><td>n=0</td><td></td><td></td><td>$\theta_0 =$</td><td>-</td></tr>
<tr><td rowspan="4">n=1</td><td></td><td></td><td>$\theta_{1,a} =$</td><td></td></tr>
<tr><td></td><td></td><td>$\theta_{1,b} =$</td><td></td></tr>
<tr><td></td><td></td><td>$\theta_{1,c} =$</td><td></td></tr>
<tr><td></td><td></td><td>$\theta_{1,d} =$</td><td></td></tr>
<tr><td rowspan="4">n=2</td><td></td><td></td><td>$\theta_{2,a} =$</td><td></td></tr>
<tr><td></td><td></td><td>$\theta_{2,b} =$</td><td></td></tr>
<tr><td></td><td></td><td>$\theta_{2,c} =$</td><td></td></tr>
<tr><td></td><td></td><td>$\theta_{2,d} =$</td><td></td></tr>
<tr><td rowspan="4">average of n=1 and n=2 values</td><td></td><td>-</td><td>-</td><td></td></tr>
<tr><td></td><td>-</td><td>-</td><td></td></tr>
<tr><td></td><td>-</td><td>-</td><td></td></tr>
<tr><td></td><td>-</td><td>-</td><td></td></tr>
</table>

Two character code of cell:

Identification of Gas:

Table 10.2: Diffraction of Light from Gas Tube - Data and Calculations

Order	Colour	Angle ($^\circ$ *and* $'$)	Angle ($^\circ$ *only*)	$\lambda = dsin(\theta_{1,x} - \theta_0)/n$
n=0			$\theta_0 =$	-
n=1			$\theta_{1,a} =$	
			$\theta_{1,b} =$	
			$\theta_{1,c} =$	
			$\theta_{1,d} =$	
n=2			$\theta_{2,a} =$	
			$\theta_{2,b} =$	
			$\theta_{2,c} =$	
			$\theta_{2,d} =$	
average of n=1 and n=2 values		-	-	
		-	-	
		-	-	
		-	-	

Two character code of cell:

Identification of Gas: